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BY

H. NORMAN ABRAMSON

FINAL

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PREPARED FOR

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APPROVED:



H. Norman Abramson, Director
Department of Mechanical Sciences

NASA CR-50,258

ABSTRACT

This report presents a review of work accomplished under the present contract, covering the period 28 March 1960 through 31 May 1963, and is based on summaries of the published papers and reports. Recommendations for future research are also given.

INTRODUCTION

Problems of fuel sloshing in launch vehicles have been of obvious importance for a long time. Much effort has been devoted to the theoretical and experimental determination of natural frequencies in a wide variety of tank configurations and to the effects of the sloshing liquid mass on the vehicle flight dynamics. Similarly, a significant amount of effort has also been devoted to exploratory studies of the effectiveness of a wide variety of baffle configurations. So extensive have all of these efforts been that it is generally feasible to include the effects of sloshing propellants in analyses of vehicle flight dynamics, at least insofar as normal sloshing behavior is concerned.

Unfortunately for the rocket designer, liquid propellants in rocket tanks may exhibit a wide variety of dynamic behavioral characteristics, oftentimes constituting problems essentially different from normal sloshing action. Further, actual flight vehicles, with the ever increasing demand for reduced structural weight and consequent increased structural flexibility, give rise to additional classes of problems by virtue of interactions between the sloshing liquids and the elastic structure.

The present research program was originated with the idea that it would consist of a series of exploratory efforts, directing attention into new and potentially important problem areas. Accordingly, a significant amount of the early effort was directed to the effects of tank draining and

liquid rotational instability on slosh characteristics, and to the effects of sloshing on heat transfer for actual and simulated cryogenic liquids. Later efforts in the program were directed toward the overall problem of interaction between the liquid propellant and the elastic structure. It soon became evident that these combined liquid-structure problems are of great potential importance and are of an extremely complex nature, and accordingly, the overall program gradually resolved itself into a study of this problem. It is perhaps essential to note, in connection with these particular studies, that the role of nonlinearities is of great importance. These may govern certain specific problems, which manifest themselves in terms of instability of the liquid motions or through modification of the tank elastic dynamic response.

It is hoped that the work accomplished under this program, and summarized in this report, demonstrates the essential role of nonlinearities and the complex nature of the liquid-structure interaction problem inherent in the design and construction of launch vehicles. This program of research has involved extensive laboratory studies and related theoretical analyses, and is to be continued under another contract. This report presents a review of work accomplished in this program by means of summaries of published papers and technical reports issued under this contract and contains some general recommendations for future research.

SUMMARIES OF PUBLISHED PAPERS AND TECHNICAL REPORTS

1. "Discussion of Production of Rotation in a Confined Liquid Through Translational Motion of the Boundaries" by Guido E. Ransleben, Jr., and H. Norman Abramson, Journal of Applied Mechanics, 27, p. 365, June 1960.

Reference is made to early SwRI experimental data demonstrating that the experimental boundaries for rotational instability of the liquid free surface are influenced strongly by the quality of the test apparatus.

2. "Some Studies of Liquid Rotation and Vortexing in Rocket Propellant Tanks" by H. Norman Abramson, Wen-Hwa Chu, Luis R. Garza and Guido E. Ransleben, Jr., Tech. Rept. No. 1, December 1960 (also, NASA Technical Note D-1212, January 1962).

This report presents the results of some experimental and theoretical studies of vortex formation while draining fluid from cylindrical tanks, and related liquid dynamic behavior. The experimental studies are largely visual, through motion picture films, but even so reveal many interesting details of vortex formation and behavior, and also include some data on time required for draining with various fluids, tank bottom shapes, and slosh and vortex suppression devices. An analytical study of vortex formation in cylindrical tanks is also presented in an attempt to understand and delineate better the flow mechanisms involved. It is concluded from the present study that while our basic knowledge of vortex formation and behavior is quite meager, baffles and similar devices can easily be provided that will allow the maintenance of adequate flow rates.

3. "An Exploratory Study of the Effect of Sloshing on Heat Transfer in a Simulated Cryogenic Liquid" by H. Norman Abramson, Luis R. Garza and William Squire, Tech. Rept. No. 2, February 1961.

Small scale tests of the effect of sloshing on the rate of evaporation of a liquid at its boiling point

showed increases of up to 50%, the largest increase occurring at frequencies which excited a rotational mode of the liquid motion; however, the variation of the rate of vaporization with temperature difference was anomalous, even in the absence of sloshing. The transfer of heat from the body of the liquid (which is superheated above the nominal boiling point) to the surface, where the vaporization takes place, appears to be an important factor in determining the rate of evaporation. Until details of the heat transfer mechanisms involved are clarified, it does not seem to be possible to deduce and completely understand the behavior in full scale tanks from tests with small models.

4. "A Discrepancy in the Published Results on Heat Transfer to Cryogenic Fluids" by William Squire, Int. Journal of Heat and Mass Transfer, 3, p. 347, (1961).

The purpose of this communication is to call attention to conflicting experimental results on heat transfer to cryogenic fluids. The problem is of some importance in connection with the design of rockets using liquid hydrogen and/or oxygen as propellants.

5. "Breathing Vibrations of a Circular Cylindrical Shell With an Internal Liquid" by Ulric S. Lindholm, Daniel D. Kana and H. Norman Abramson, Tech. Rept. No. 3, February 1962 (also, Journal of the Aerospace Sciences, 29, pp. 1052-1059, September 1962).

Resonant breathing frequencies and mode shapes are determined experimentally for a thin-walled circular cylindrical shell containing a nonviscous incompressible liquid. The resonant frequencies determined for the full shell are in good agreement with those predicted by Reissner's shallow-shell vibration theory with the inclusion of an apparent-mass term for the liquid. The effect of the internal liquid on the shell mode shapes is significant only for the partially full shell. In this case the circumferential node lines tend to shift toward the bottom or filled portion of the shell.

Excitation of low-frequency liquid-sloshing motion by high-frequency forced oscillation of a partially filled shell occurred in many cases. This low-frequency liquid response is tentatively explained as being

excited by a beat frequency in the forced oscillation. A similar type of response has been reported by Yarymovych in axially excited rigid tanks.

6. "Bending Vibrations of a Circular Cylindrical Shell Containing an Internal Liquid With a Free Surface" by Ulric S. Lindholm, Wen-Hwa Chu, Daniel D. Kana and H. Norman Abramson, Tech. Rept. No. 4, March 1962 (also, preprint paper 63-24, IAS Annual Meeting, January 1963, to appear in the AIAA Journal).

Resonant bending frequencies and mode shapes were determined experimentally for a thin circular cylindrical shell containing an internal liquid with a free surface. The measured increase in frequency between uncapped and capped partially filled tanks of two different end conditions are generally in agreement with theoretical predictions. Differences between theory and experiment are attributed primarily to variations of actual mode shapes from those assumed in the theory. This is true for both cantilever and pin-ended tanks, with the latter being even more complicated by a strong dependence of mode shape on liquid depth. Significant coupling occurred between bending and breathing shell responses, becoming increasingly important with decreasing tank fineness ratio.

7. "An Experimental Study of Liquid Instability in a Vibrating Elastic Tank" by Daniel D. Kana, Ulric S. Lindholm and H. Norman Abramson, Tech. Rept. No. 5, January 1963.

The results of an experimental study of a curious instability phenomenon occurring in the response of a vibrating, partially liquid filled, elastic tank are described. The instability occurs in the neighborhood of the resonant breathing modes of the coupled system and is noted by a periodic low frequency modulation of the tank motion and a simultaneous low frequency resonance of the free surface of the liquid in a rotationally symmetric mode. Response characteristics of both the tank and liquid motion are given which demonstrate significant non-linear behavior.

8. "Longitudinal Forced Vibration of Partially Filled Tanks" by Daniel D. Kana, Tech. Rept. No. 6, February 1963.

This report presents the results of a study of the longitudinal forced vibration of tanks containing liquids of arbitrary depth, and includes some of the most significant individual aspects that occur throughout a wide range of excitation frequencies. Since three basic areas are involved, the liquid system, the tank system, and the coupled liquid-tank system, for simplicity a liquid system in a rigid tank is discussed first, and then the more realistic liquid-elastic tank system afterward. Liquid surface resonance, capillary wave behavior, and bubble behavior and cavitation in a rigid tank are considered. These areas are again discussed, as they occur for the elastic tank, along with the behavior of the liquid-elastic tank system. The occurrence of subharmonic tank breathing modes, and the production of low frequency liquid surface resonances by high frequency tank breathing motion are noted and attributed to instabilities occurring in the coupled liquid-elastic tank system. In general, it is found that the overall problem involves various areas in which only a nonlinear analysis is feasible even to obtain qualitative information. Unfortunately, the usual difficulties of a nonlinear approach are even magnified here because of the coupling between two complex systems.

9. "Breathing Vibrations of a Partially Filled Cylindrical Tank—Linear Theory" by Wen-Hwa Chu, Journal of Applied Mechanics, to appear.

An accurate linear hydrodynamic theory (incompressible) is presented for breathing vibrations of a liquid column with an assumed mode shape. It yields the natural frequencies of liquid sloshing as well as the pressure distribution. A simplified frequency prediction for the partially filled cylindrical shell is derived from the Donnell-Yu equation with an apparent mass correction. Comparison with some available experiments shows good agreement for breathing vibrations with the fundamental longitudinal mode.

DISCUSSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

The results of this research program have demonstrated the sometimes overriding importance of system nonlinearities in governing the general behavior of liquid propellants in elastic tanks. Carefully conducted laboratory experiments have demonstrated these phenomena quite vividly; unfortunately, our analytical ability to explain and predict such nonlinear behavior is rather drastically limited, and accordingly, much increased emphasis must be placed on the theoretical analysis of nonlinear liquid dynamic behavior. The practical importance of these phenomena in applications of actual launch vehicles is as yet somewhat unclear; however, in view of the laboratory demonstration of their occurrence, careful attention should be given to data from future launch vehicle flight programs in an effort to detect any tendency of any such phenomena in practice.

With the tremendous increase in size of launch vehicles now contemplated, it is essential, for a number of reasons, that careful attention be given to these types of problems in future research. Specific recommendations for future research are difficult to formulate because of the presently intensive level of activity in this problem area by a very large number of agencies and organizations. However, the following problem areas certainly appear to be well worthy of further research:

1. Theoretical analysis of nonlinear coupling phenomena
between elastic shell breathing vibrations and contained

liquids.

2. Careful experimental and theoretical studies of the occurrence of subharmonic oscillations in tanks of varying geometry under a variety of excitation conditions.
3. Increased attention should be given to problems of axial excitation of tanks of varying geometry, with emphasis on liquid surface resonance, capillary wave behavior, and bubble formation and cavitation.

ACKNOWLEDGEMENTS

The authors of the various papers and reports prepared under this program wish to express their appreciation to their many colleagues who provided so much valuable assistance during the course of the various studies. Particularly, thanks are due Messrs. W. L. Mynatt, F. R. Carter, and D. C. Scheidt for assistance in the experimental work, Mr. Gilbert F. Rivera for preparing all figures and drawings, Miss D. Nolen, Mrs. N. Powell, and Mrs. S. Cloer for typing and other services, and the entire staff of the SwRI Computations Laboratory.

APPENDIX A

RELATED RESEARCH PROGRAMS AT SwRI

The general research program covered in this report is being continued under Contract No. NASr-94(03). Work on this Contract, initiated on 1 April 1963, is being devoted to theoretical and experimental studies of nonlinear response of liquids in rigid and elastic containers.

A closely related program, initiated on 25 March 1961, is being carried out under Contract No. NAS8-1555 with the Marshall Space Flight Center of NASA. Technical reports prepared under this contract are listed in Appendix B of the present report. Present efforts are being directed toward the accumulation of data on baffling effectiveness for use in design applications.

Design problems associated with passive anti-roll stabilization tank systems for surface ships are similar in many respects to those of propellant sloshing in rocket tanks. Work in this area is being conducted under sponsorship of the U. S. Navy BuShips Fundamental Hydromechanics Research Program, administered by the David Taylor Model Basin under Contract No. Nonr-3926(00).

APPENDIX BRELATED TECHNICAL REPORTS AND
PUBLISHED PAPERS PREPARED BY SwRI

U. S. ARMY ORDNANCE CORPS, ARMY BALLISTIC MISSILE AGENCY
(Contract DA-23-072-ORD-1062)

1. "Dynamic Loads Resulting From Fuel Motion in Missile Tanks" by Thomas B. Epperson and Robinson Brown, Final Report, June 1957.
2. "Dynamic Loads Resulting From Fuel Motion in Missile Tanks" by Thomas B. Epperson, Robinson Brown and H. Norman Abramson, Advances in Ballistic Missile and Space Technology, 2, pp. 313-327, Pergamon Press, New York, 1961.

U. S. ARMY ORDNANCE CORPS, ARMY BALLISTIC MISSILE AGENCY
(Contract DA-23-072-ORD-1251)

1. "Application of Similitude Theory to the Problem of Fuel Sloshing in Rigid Tanks" by H. Norman Abramson, Robert J. Martin and Guido E. Ransleben, Jr., Tech. Rept. No. 1, May 1958.
2. "Sloshing of Liquids in Cylindrical Tanks of Elliptic Cross-Section" by Wen-Hwa Chu, Tech. Rept. No. 2, September 1958 (also, ARS Journal, 30, pp. 360-363, April 1960).
3. "Simulation of Fuel Sloshing Characteristics in Missile Tanks by Use of Small Models" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 3, March 1959.
4. "Some Comparisons of Sloshing Behavior in Cylindrical Tanks With Flat and Conical Bottoms" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 4, May 1959 (also, ARS Journal, 31, pp. 542-544, April 1961).
5. "A Note on Wall Pressure Distributions During Sloshing in Rigid Tanks" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 5, June 1959 (also, ARS Journal, 31, pp. 545-547, April 1961).

6. "A Note on the Effectiveness of Two Types of Slosh Suppression Devices" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 6, June 1959.
7. "Simulation of Fuel Sloshing Characteristics in Missile Tanks By Use of Small Models" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 7, April 1960 (also, ARS Journal, 30, pp. 603-612, July 1960).
8. "Representation of Fuel Sloshing in Cylindrical Tanks by an Equivalent Mechanical Model" by H. Norman Abramson, Wen-Hwa Chu and Guido E. Ransleben, Jr., Tech. Rept. No. 8, June 1960 (also, ARS Journal, 31, pp. 1697-1705, December 1961).
9. "Free Surface Condition for Sloshing Resulting From Pitching and Some Corrections" by Wen-Hwa Chu, ARS Journal, 30, pp. 1093-1094, November 1960.
10. "Total Force Response Resulting From Liquid Sloshing in a Rigid Cylindrical Tank With a Vertical Center Wall Baffle" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 9, May 1961.
11. "Some Studies of a Floating Lid Type Device for Suppression of Liquid Sloshing in Rigid Cylindrical Tanks" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 10, May 1961.
12. "Liquid Sloshing in Rigid Cylindrical Tanks Undergoing Pitching Motion" by H. Norman Abramson and Guido E. Ransleben, Jr., Tech. Rept. No. 11, May 1961.
13. "Theoretical and Experimental Studies of Liquid Sloshing in Rigid Cylindrical Tanks" by H. Norman Abramson, Final Report, May 1961.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION---MARSHALL
SPACE FLIGHT CENTER (Contract NAS8-1555)

1. "Some Notes on Liquid Sloshing in Compartmented Cylindrical Tanks" by H. Norman Abramson, Luis R. Garza, and Daniel D. Kana, Tech. Rept. No. 1, February 1962 (also, ARS Journal, 32, pp. 978-980, June 1962).

2. "Liquid Sloshing in Spherical Tanks" by H. Norman Abramson, Wen-Hwa Chu and Luis R. Garza, Tech. Rept. No. 2, March 1962 (also, AIAA Journal, 1, pp. 384-389, February 1963).
3. "Liquid Sloshing in 45° Sector Compartmented Cylindrical Tanks" by H. Norman Abramson, Wen-Hwa Chu and Luis R. Garza, Tech. Rept. No. 3, November 1962.
4. "Liquid Sloshing in a Spherical Tank Filled to an Arbitrary Depth" by Wen-Hwa Chu, Tech. Rept. No. 4, December 1962.
5. "Measurements of Liquid Damping Provided by Ring Baffles in Cylindrical Tanks" by Luis R. Garza and H. Norman Abramson, Tech. Rept. No. 5, April 1963.
6. "A Brief Comparison of Ring and Asymmetrical Baffle Characteristics" by Luis R. Garza, Tech. Rept. No. 6, April 1963.
7. "A Preliminary Analysis for Optimum Design of Ring and Partition Antislosh Baffles" by Carl G. Langner, Tech. Rept. No. 7, April 1963.

GENERAL

1. "Amazing Motions of Liquid Propellants" by H. Norman Abramson, Astronautics, 6, pp. 35-37, March 1961.
2. "Liquid Dynamic Behavior in Rocket Propellant Tanks" by H. Norman Abramson, ONR/AIA Symposium on Structural Dynamics of High Speed Flight, pp. 287-318, Los Angeles, April 1961.
3. "The Falling Pendulum" by William Squire, ARS Journal, 32, pp. 263-264, February 1962.
4. "Some Recent Developments Concerned With Liquid Dynamic Behavior in Moving Containers" by H. Norman Abramson, invited lecture, ASME Applied Mechanics Division Annual Conference, Cornell University, June 1963 (also, Applied Mechanics Reviews, to appear).